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Paper 002

SOLAR-POWERED ROCKET ENGINE OPTIMIZED FOR HIGH SPECIFIC IMPULSE

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ABSTRACT

Hercules Aerospace is currently developing a solar-powered rocket engine (SPRE) design optimized for high specific impulse (Isp). The SPRE features low loss geometry in its light-gathering cavity, which includes an integral secondary concentrator. The simple one-piece heat exchanger is made from refractory metal and/or ceramic open-celled foam. The foam's high surface-area-to-volume ratio will efficiently transfer thermal energy to the hydrogen propellant. The single-pass flow of propellant through the heat exchanger further boosts thermal efficiency by regeneratively cooling surfaces near the entrance of the optical cavity. These surfaces would otherwise reradiate a significant portion of the captured solar energy back out the cavity entrance. Such design elements promote a high overall thermal efficiency and hence, a high operating Isp.

INTRODUCTION

Modern space launch vehicles place less than 1% of their ground launch mass into geosynchronous earth orbit (GEO), where fully two-thirds of all satellites launched reside. This low delivered payload fraction translates to high delivery costs ranging between $33,000 to$220,000/kg ($15,000 to $100,000/lb) to GEO. Solar-thermal propulsion offers an attractive alternative to reducing orbit transfer costs. A comparison of solar-thermal with other conventional and other advanced propulsion concepts is shown in Table 1 for transfer from LEO to GEO based on a starting LEO payload of 1000 lb.

Solar-thermal propulsion is based on using compact mirrors that collect and focus sunlight into a light capturing cavity. A heat exchanger is located within the cavity walls. Propellant passing through the heat exchanger is heated to thousands of degrees and directed out of a nozzle, creating thrust at high Isp. High efficiencies promote small lightweight and cost-efficient energy collection methods. A delivered Isp in the 7846 to 9317 N-sec/kg (800 to 950 lbf-sec/lbm) range appears to be achievable.

The solar-powered rocket engine (SPRE) concept has been demonstrated. Hercules approach to improving the SPRE concept includes three novel improvements: use of an integral secondary concentrator, employment of optimized cavity geometry, and the use of a foam-type heat exchanger.[1] The integral secondary concentrator is located at the SPRE cavity entrance. It accepts direct and diffused focused sunlight from the primary mirror. The concentrator refocuses sunlight deep into the cavity as well as reduces re-radiation out the entrance as a result of its smaller diameter. The optimized "ogive" cavity geometry is designed to accept focused energy from the secondary concentrator. Its shape directs energy into the deepest recesses, minimizing direct surface re-radiation out of the cavity entrance. A double-walled foam heat exchanger surrounds the light capturing cavity. Its inner wall forms the light capturing cavity wall. The foam heat exchanger allows heat to be passed to the hydrogen propellant quickly and efficiently. The single-pass nature of the heat exchanger allows for regenerative cooling of surfaces that are most exposed to the entrance, minimizing re-radiation losses.

Propulsion Type	Fuel	Specific Impulse		Thrust		Thermal Efficiency[a] (%)	Fuel Mass[b]		Inert Mass[c]		Payload to GEO		Time to GEO (days)
		N-sec/kg	lbf-sec/lbm	N	lbf		kg	lbm	kg	lbm	kg	lbm	
Solid													
• Conventional	HTPB	2,942	300	8,896	2,000	--	347	765	75	164	32	71	1
Liquid													
• Cryogenic	LOX/H_2	4,226	435	6,672	1,500	--	287	632	145	319	22	49	1
• Storable	N_2O_4/MMH	3,138	320	445	100	--	337	743	107	236	10	21	1
Electrothermal													
• Resistojet	NH_3	3,236	300	0.22	0.05	<10.0	391	863	154	340	0	0	180+
• Arcjet[d]	NH_3	6,620	675	0.22	0.05	<5.0	266	587	120	265	67	148	180+
• Arcjet[d]	H_2	11,768	1,200	0.22	0.05	<5.0	153	336	193	424	109	240	180+
Electrostatic													
• Ion	C_3	24,518	2,500	0.22	0.05	<8.0	96	212	206	455	151	333	180+
Electromagnetic													
• MPD	NH_3	14,710	1,500	0.22	0.05	<5.0	149	328	324	714	0	0	180+
Solar-Thermal	H_2	8,434	860	4.4	1.0	>60.0	198	435	59	130	198	435	15
Nuclear-Thermal[e]	H_2	8,581	875	--	--	--	--	--	--	--	--	--	--

HTPB = hydroxy-terminated polybutadiene solid propellant.
MMH = monomethylhydrazine.

a. Percentage of sunlight energy converted to kinetic energy of exhaust gases.
b. Fuel mass estimated for total starting mass of 454 kg (1000 lbm) in 232 km (125 nmi) altitude circular LEO, inclined 28.5°, and delivering payload to GEO.
c. Guidance, navigation, and control mass required to perform orbit transfer is not included in the inerts.
d. Low power arcjet specific impulse performance. Hydrogen arcjet performance can vary between 7846-14711 N-sec/kg (800-1500 lbf-sec/lbm) Isp.
e. Insufficient information to estimate nuclear-thermal mass fractions and payload performance for this relatively low payload mass mission.

Table 1. Solar-thermal propulsion delivers the greatest payload from LEO to GEO.

SPRE BASELINE DESIGN DESCRIPTION

Figure 1 illustrates the design and operation of the Hercules SPRE baseline design. For purposes of light gathering, the SPRE is comprised of a conical section through which solar radiation enters the engine, secondary concentrator section, and ogive solar collection cavity.

For the heating of propellant, a double-wall, single-pass heat exchanger surrounds the cavity. Between the double walls is an open-celled foam heat exchanger media that heats the propellant as it passes. The propellant is expanded through a converging/diverging nozzle to produce thrust.

Pressurized hydrogen propellant enters through a single tube (located at the forward end) and passes into an annular manifold cavity. The annular manifold cavity evenly distributes propellant before it enters the conical section of the engine. The conical section represents the first section of a continuous single-pass foam heat exchanger. Focused sunlight (received from an external concentrating mirror) enters the large aperture of the conical section. The apex angle of the conical section is approximately equal to the apex angle of the incoming focused sunlight. Stray sunlight impinging on the conical section will be absorbed by the inner wall. The heated wall, in turn, passes energy to the foam heat exchanger, regeneratively cooling the inner wall.

Once propellant has traveled through the conical section, it proceeds to the secondary concentrator section. The secondary concentrator inside surface is optically reflective. It will receive focused solar energy, concentrate it, and then pass it into the ogive cavity section. The reflective surface is regeneratively cooled by propellant.

As propellant leaves the secondary concentrator section, it enters the ogive section. The ogive section is a trapped cavity design. The entrance has an increasing aperture in the direction of propellant flow. This allows light received from the secondary concentrator to pass deep into the ogive region, minimizing reflections and re-radiation losses. The apex angle formed by the entrance section of the ogive cavity can vary greatly (10° half angle shown), depending on many factors, including solar thermal energy apex angle, flux magnitude, and distribution conditions at the entrance of the solar thermal propulsion device. The ogive has a decreasing aperture in the direction of propellant flow, made up of spherical radius geometries (sections of a circle). Heated propellant leaving the ogive section enters the converging section of a converging/diverging rocket nozzle, through the porous foam surface. Propellant gases are then expanded and accelerated out the nozzle, creating thrust at high Isp.

The hydrogen-fueled SPRE does not operate like a conventional liquid chemical rocket engine because no combustion takes place. Hydrogen gains internal energy in the form of temperature (2343°C [4250°F] typical peak temperature) while passing through the foam heat exchanger. It then converts its internal energy into kinetic energy as it expands and accelerates out of the nozzle.

Figure 2 illustrates the reduced aperture area afforded by the secondary concentrator. The axisymmetric device accepts focused and diffuse solar energy at its largest aperture, concentrating and directing solar energy through the small aperture and into the ogive cavity. Solar radiation originating from the primary mirror is focused at a point along the engine centerline, approximately in the middle of the secondary concentrator section. The focus location is shown at the point of intersection of the two diagonal dashed lines. Unreflected solar radiation will pass directly into the ogive cavity.

Any reticulated open-celled foam that is capable of withstanding the thermal and structural environments and compatible with the propellant may be used as the exchanger medium. The high surface-area-to-volume ratio open-celled foam provides high conductive and convective heat exchange rates per unit volume. This is especially important for propellants like hydrogen that are virtually incapable of absorbing radiant thermal energy directly. The convoluted path of the

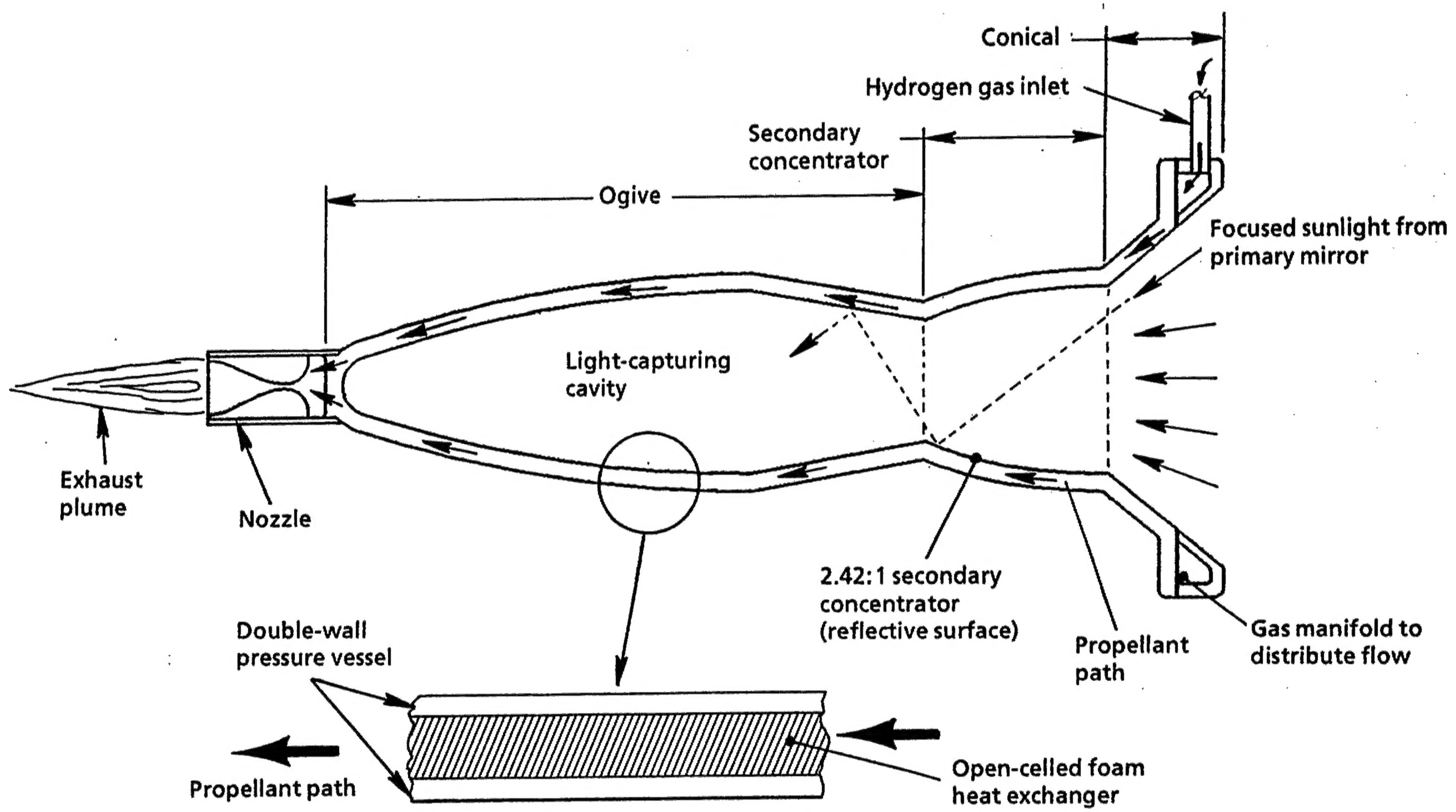

Figure 1. Hercules baseline SPRE design

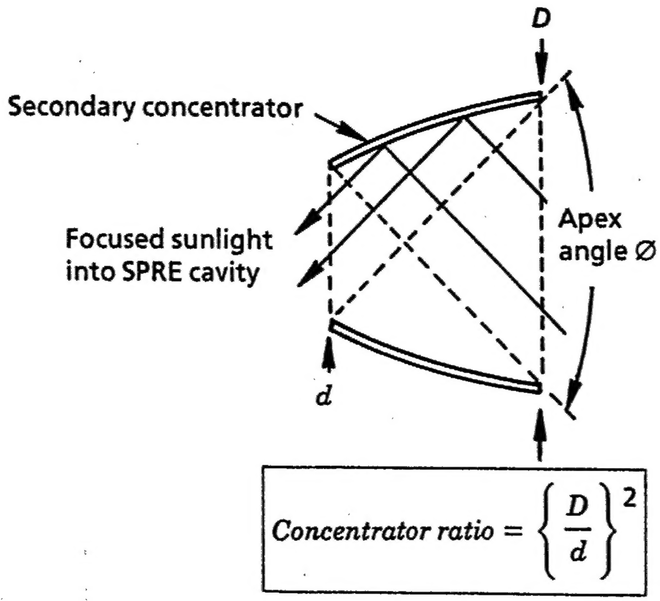

Figure 2. The secondary concentrator captures focused or diffuse light, concentrating it and directing it to the ogive cavity.

propellant through the open-cell foam medium promotes turbulence, increasing the heat exchange rate.

During SPRE operation, pressurized propellant passes through the foam heat exchanger. The effects of pressurization are manifest as large stresses in the double walls. The inner wall goes into compression, while the outer wall is in tension. To minimize wall stress (to allow reduced wall thickness), the foam can be made to carry much of the pressure loads, offloading the wall. By attaching the foam structure to both walls, it can be made to carry pressure loads between walls.

Generally, the propellant fluid will be stored in a tank compatible with the propellant and transported through pipes to the SPRE. A solar collection and focusing means or "concentrating mirror" collects solar radiation and focuses into the SPRE cavity. High heat insulating, low heat conducting materials are placed outside the SPRE heat exchanger to prevent heat loss. High porosity RVCF is ideally suited for this purpose and may be coated with a material such as hafnium carbide to prevent sublimation. Concentric metal radiation shields surrounding the hottest regions of the solar thermal propulsion engine minimize heat loss. These are placed between the outer walls of the cavity and the foam insulation. A support structure ties the SPRE and its thermal insulation system together. Additionally, it forms an interface with or attaches the engine to the orbital transfer vehicle structure. The structure may be as simple as a lightweight cylinder that encloses engine and thermal insulation system and may be equipped with standoffs to attach to the orbit transfer vehicle, a fuel line connector, or a thrust vector control mechanism.

The foam medium can be manufactured by coating or converting commercially available reticulated vitreous carbon foam (RVCF). The RVCF acts as the substrate, defining geometry. RVCF can be coated with refractory metals such as tungsten (W) and rhenium (Re) or ceramic carbides, including hafnium carbide (HfC), zirconium carbide (ZrC), tantalum carbide (TaC), and others. The foam substrate can also be converted directly into a carbide (hafnium metal + RVCF carbon to form HfC). Selection of materials should be based on operating temperatures, pressures, and propellant species. Hydrogen at high temperature compromises the structural integrity of most materials.

Hafnium carbide and zirconium carbide are useful without coating at temperatures below about 2671°C (4840°F) and 2638°C (4780°F), respectively, but require a refractory metal coating for use at higher temperatures. Tantalum carbide reacts with hydrogen at lower temperatures than those materials and will normally need to be coated with refractory metal to be used in a heat exchanger.

For ease of manufacture, the entire open-cell foam heat exchanger can be fabricated from a single block of RVCF substrate. It may also be made from one or more pieces by connecting parts; e.g., using an adhesive containing foam parent material. The foam can be machined to the geometrical contour of each section. The foam section that forms the annular manifold cavity can be formed by internal removal of foam material (e.g., by machining) or by bonding a separate piece of foam.

The open-celled RVCF preform may be coated with the refractory metal rhenium, using chemical vapor infiltration (CVI) methods. The inner and outer pressure containment walls are then formed around and integrally attached to the foam using rhenium chemical vapor deposition (CVD) methods. Rhenium is essentially inert to a hydrogen propellant environment, chemically compatible (up to the eutectic) to the underlying carbon, and very ductile.

To prevent sublimation of the heated inner wall of the cavity resulting from exposure to high temperature in a vacuum, the cavity is pressurized ($>8.0 \times 10^{-3}$ mm Hg) above the vapor pressure of rhenium. This can be done by injecting propellant from the cavity wall or pumping propellant from the hydrogen storage unit into the cavity. It is also possible to collect nozzle expansion (Prandtl-Meyer and boundary layer) gases leaving the nozzle exit plane that have turned significantly relative to the engine centerline. These gases do not contribute to deliverable specific impulse. By means of a scroll (donut-shaped collection cavity with an annular inlet slit) located just outboard of the nozzle exit plane, these gases can be collected and directed (using piping) inside the cavity, slightly pressurizing the local atmosphere to prevent sublimation. Radiation shields, insulation, and other heated components can also be slightly pressurized to prevent sublimation, but not to the point of affecting thermal performance.

The Hercules SPRE concept incorporates a patented design with the use of advanced materials. This combination results in high efficiency and high specific impulse. In combination with an orbital transfer vehicle, the Hercules SPRE concept should increase LEO-to-GEO payload fraction two-fold.

HERCULES SPRE DEVELOPMENT PROGRESS

Hercules is currently conducting studies leading to demonstration of a full-scale SPRE.

REFERENCES

1. United States Patent No. 5,138,832 titled "Solar-Thermal Propulsion Engine."